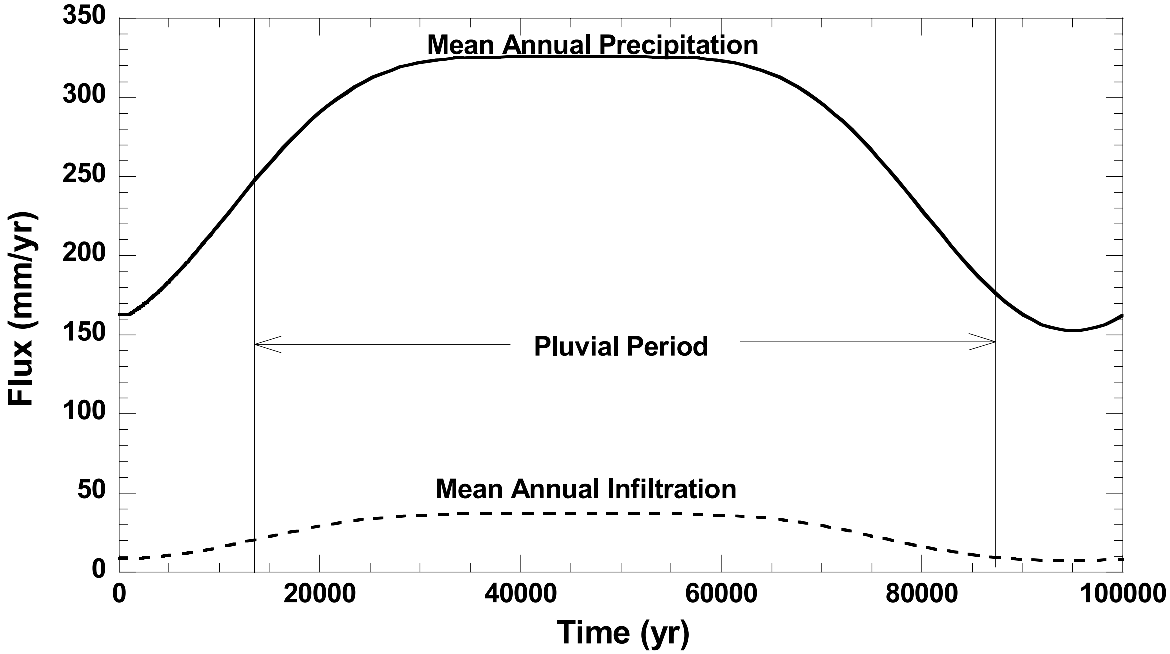

Figure 4-30. Predicted Mean Annual Precipitation and Infiltration at the Repository Horizon Averaged Over All Subareas and Encompassing both the Current and Pluvial Periods for the Mean Value Data Set (Mohanty, et al., 2002, Figure 3-1)

4.3.7 Radionuclide Transport in the Unsaturated Zone (UZ3)

Risk Insights:	
Retardation in the Calico Hills nonwelded vitric Unit	Medium Significance
Matrix Diffusion in the Unsaturated Zone	Medium Significance
Effect of Colloids on Transport in the Unsaturated Zone	Medium Significance

4.3.7.1 Discussion of the Risk Insights

Retardation in the Calico Hills Nonwelded Vitric Unit: Medium Significance to Waste Isolation

Retardation in the Calico Hills nonwelded vitric unit has the potential to delay the movement of most radionuclides for very long time periods (e.g., thousands to tens of thousands of years and longer) for nuclides that tend to sorb onto rock surfaces (e.g., Np-237, Am-241, and Pu-240).

Certain nuclides do not readily sorb onto rock surfaces (i.e., I-129 and Tc-99). Where the Calico Hills nonwelded vitric unit is present below the repository, sorption of radionuclides may limit releases to the saturated zone, within the compliance period, to insignificant quantities for all radionuclides except I-129 and Tc-99. In this context the retardation factor for Np-237 is the most significant because of the large inventory and long half-life for this radionuclide.

Discussion

Retardation in the Calico Hills nonwelded vitric unit has the potential to delay the transport of sorbing radionuclides for time periods on the order of 10,000 years and beyond. Table 4-7 shows the effect of the range of retardation in the Calico Hills nonwelded vitric unit on the transport time for key radionuclides through the unsaturated zone to the water table (i.e., saturated zone). Radionuclides that do not readily sorb onto rock surfaces (i.e., I-129 and Tc-99) show limited delay time (i.e., 450 years) relative to sorbing or retarded radionuclides (i.e., Np-237, Am-241, and Pu-241) where releases are delayed on the order of 10,000 years for low retardation factors and significantly greater for high retardation factors. It is important to note that nonsorbing radionuclides such as I-129 and Tc-99 represent a small fraction (less than 1 percent) of the overall inventory of the potential repository, whereas sorbing radionuclides, such as Np-237, Pu-240, and Am-241 represent a large fraction (greater than 99 percent) of the inventory (Table 4-1) (McCartin, 2003).

Uncertainties

The proclivity for matrix flow in the high-conductivity Calico Hills nonwelded vitric unit is key to the significant retardation provided by this unit. As described in Section 4.3.6, the areal extent and thickness of the Calico Hills nonwelded vitric unit between the potential repository and the water table are important uncertainties.

Matrix Diffusion in the Unsaturated Zone: Medium Significance to Waste Isolation

Matrix diffusion may have an effect on delaying radionuclide transport in the unsaturated units where the water flow is primarily in fractures.

Table 4-7. Saturated Zone
Retardation Sensitivity (Calico Hills Nonwelded Vitric Unit)
(Years for Initial Release into Unsaturated Zone to Exit Unsaturated Zone)

Nuclide	Rf (low)	Rf (high)
Tc-99	450	450
I-129	450	450
Np-237	9,000	60,000
AM-241	>100k	>100K
Pu-240	>100K	>100K

Discussion

Radionuclides transported within fractures may be delayed because of diffusion from the fracture water into matrix water (i.e., matrix diffusion) when radionuclide concentrations are higher within the fracture water versus the matrix water. This process will affect all radionuclides. However, radionuclides that sorb onto rock surfaces (i.e., are retarded) will show longer delays than those radionuclides that are not sorbed. The NRC modeling approach in TPA Version 4.1 code for unsaturated zone flow and transport estimates matrix diffusion is likely minor in fractured tuffs in the unsaturated zone because the estimated effect in the saturated zone is also limited (Winterle, et al., 1999, Figure 2-3). However, the DOE sensitivity analyses for matrix diffusion in the unsaturated zone indicate that a significant reduction in the simulated dose-rate history occurs when credit is taken for matrix diffusion (CRWMS M&O, 2000b, Figure 5.2-14). Figure 4-31 shows the reduction is highly time-dependent and ranges from a factor of 2 to more than a factor of 10. Another example of the effects of including matrix diffusion in the unsaturated zone transport model is provided by the impact of the Topopah Spring welded tuff unit (flow primarily in fractures) on the short traveltimes for ground water through the unsaturated zone. DOE sensitivity studies indicate that traveltimes are reduced by an order of magnitude when matrix diffusion is not included for the TSw unit (Eddebbarh, et al., 2000).

Uncertainties

The process of matrix diffusion is uncertain because of complexities of the interaction of potentially fast-moving water (e.g., meters per year) in fractures with the matrix water. Differences in the chemistries of fracture water and matrix water suggest that the interactions between fracture and matrix water may not be very significant (Murphy and Pabalan, 1994).

Effect of Colloids on Transport in the Unsaturated Zone: Medium Significance to Waste Isolation

Transport of radionuclides attached to natural colloids may reduce the effectiveness of sorption properties of the Calico Hills nonwelded vitric unit.

Discussion

Radionuclides that attach to colloids have the potential to be transported in a manner that may substantially reduce or eliminate the beneficial effect of sorption in geologic materials such as the Calico Hills nonwelded vitric unit. Although performance effects have not been explicitly examined using the total system performance assessment code, the code was used to bound colloid effects by allowing unretarded transport of relatively immobile actinides such as plutonium, americium, and thorium. That conservative analysis, which assumes a bounding unretarded transport, yielded an increase in dose by more than a factor of 10 (Figure 4-21). DOE has performed analyses to evaluate the sensitivity of colloids where plutonium and americium are irreversibly sorbed to waste-form colloids (Figure 4-22). The DOE analyses indicated that colloidal concentrations were only significant in 10,000 years, under an intrusive igneous event, wherein a large number of waste packages are significantly damaged. The potential importance of colloidal transport, if all waste packages were to fail within 10,000 years, is evident in the DOE total system performance assessment for site recommendation (CRWMS M&O, 2000b), which indicated colloidal plutonium is the second highest dose contributor after 70,000 years, when a significant number of waste packages are estimated to have failed, allowing release of radionuclides.

Uncertainties

Some field studies (Kersting, et al., 1999) suggest that colloids can travel relatively easily under particular conditions, which are not expected to be relevant to transport in the unsaturated zone at Yucca Mountain. There is considerable uncertainty both with the determination of the colloidal concentration and the extent to which colloids will be transported or filtered in the geosphere as they move through small fracture openings and matrix pores.

4.3.8 Flow Paths in the Saturated Zone (SZ1)

Risk Insights:

Saturated Alluvium Transport Distance	Medium Significance

4.3.8.1 Discussion of the Risk Insights

Saturated Alluvium Transport Distance: Medium Significance to Waste Isolation

The saturated flow path is comprised of both fractured tufaceous rock and porous alluvium. Alluvium comprising a portion of the flow path is important because of the large capacity of the alluvium to retard a majority of the radionuclides. To have a significant influence on retarded radionuclides, the alluvium needs to comprise at least 500 m [1,640 ft] of the total flow path of 18 km [11.2 mi].

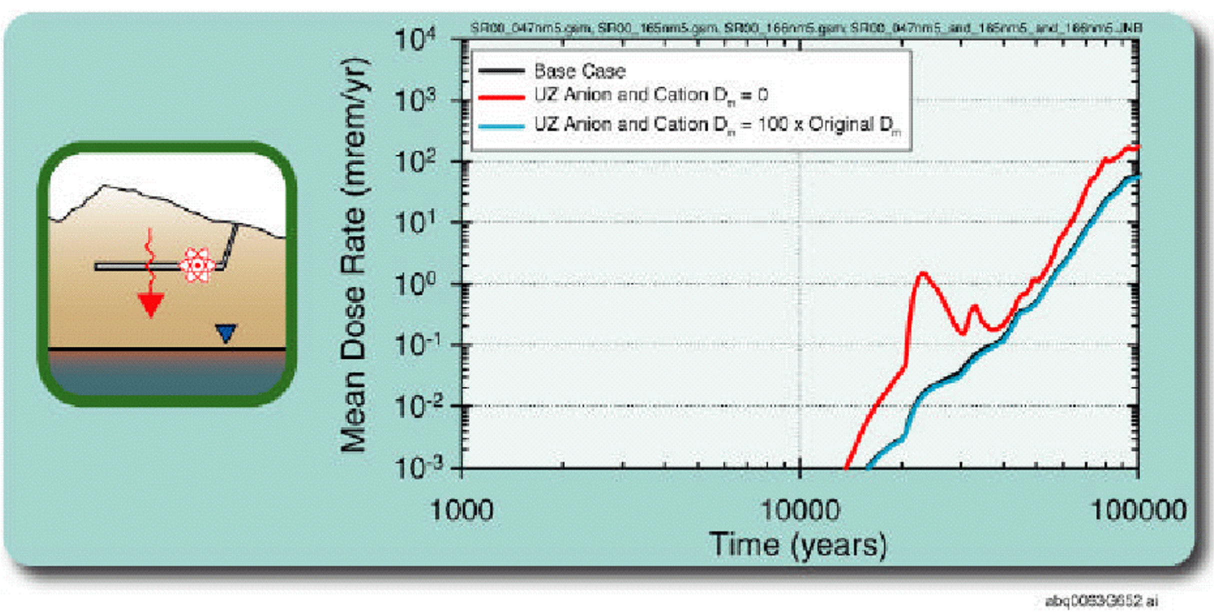

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Figure 4-31. Sensitivity to Matrix Diffusion in the Unsaturated Zone. (From CRWMS M&O, 2000b; page F5-37) (1.0 mrem/yr = 0.01 mSv/yr)

Discussion

Both fractured tufaceous rock and porous alluvium comprise the saturated flow path. The velocity of the water flow within these two units can be quite different because of differences in the hydrologic properties, specifically between the porosity of the alluvium (i.e., on the order of 15 percent of the overall volume) and the porosity of the fractured tuff (i.e., on the order of 0.1 to 1 percent of the overall volume). The unretarded radionuclide traveltime for the saturated zone is estimated to be on the order of several hundreds of years and longer (Figure 4-32). Because flow velocities in the alluvium are small relative to the fractured tuff, the majority of the traveltime is in the alluvium. Radionuclides traveling through the alluvium are especially important because of the potential capability of the porous media to delay a majority of radionuclides due to chemical sorption onto mineral surfaces. (See Section 4.3.9.) An alluvium flow path length of only 500 m [1,640 ft] {relative to a total saturated zone flow path length of 18 km [11.2 mi]} has a significant capacity to retard radionuclides (Table 4-8). Current information indicates alluvium is present for at least 2 km [1.2 mi] along the flow path.

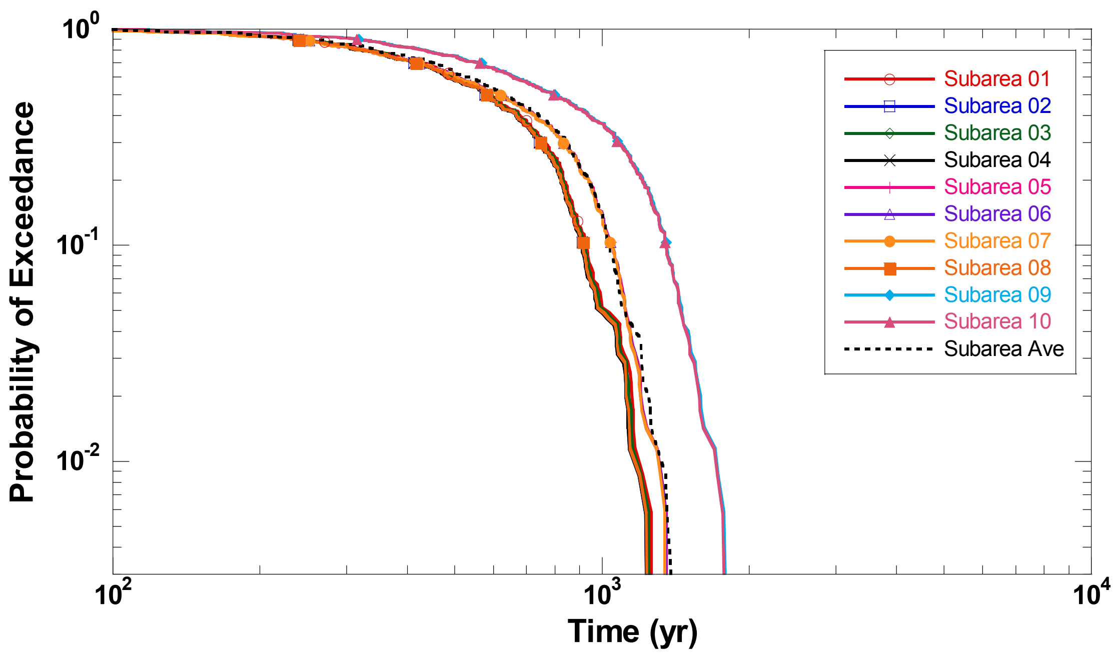


Figure 4-32. Complementary Cumulative Distribution Function of Saturated Zone Unretarded Radionuclide Traveltimes for 350 Realizations (Mohanty, et al., 2002, Figure 3-33)

Table 4-8. Saturated Zone Retardation Sensitivity (Years for Initial Release into Saturated Zone to Exit Saturated Zone)				
Nuclide	**Alluv {1 km [0.6 mi]} Rf (low)**	**Alluv {1 km [0.6mi]} Rf (high)**	**Alluv {5 km [3.1 mi]} Rf (low)**	**Alluv {5 km [3.1 mi]} Rf (high)**
Tc-99	350	350	550	550
I-129	350	350	550	550
Np-237	950	76.000	1,050	>100K
Am-241	>100K	>100K	>100K	>100K
Pu-240	54,000	>100K	>100K	>100K

Uncertainties

Based on the results shown in Table 4-8, uncertainty in the length of the flow path in the alluvium {i.e., 1 km [0.6 mi] versus 5 km [3.1 mi]} does not have a significant impact on performance, and the variation of retardation factor is significant only for Np-237. Flow within the saturated zone is affected by heterogeneity. For example, variations in structure (e.g., fault zones) and permeability (e.g., high-permeability zones) are present. Although these types of heterogeneity are expected to result in local perturbations in the flow field, the flow regime, on a regional scale, is not expected to be significantly altered. Detailed hydrological modeling studies of the saturated zone that have examined the effects of fault zones on flow and transport (Figure 4-33) indicate inclusion of additional structure in the model would affect the spreading of a contaminant plume, but would not significantly affect the unretarded radionuclide traveltime. For example, the presence of a fault tends to spread pathlines vertically (Figure 4-33a) while retaining the general leading-edge shape of the plume (Figure 4-33b).

Borehole data suggest that alluvial sediments can be strongly heterogeneous, ranging from fine-grained clay sediments to coarse gravels and sands. The effect of this heterogeneity on flow paths and traveltimes in saturated alluvium is an important uncertainty that is handled in both the DOE and NRC performance assessment models by stochastically sampling the effective porosity of alluvium. Lower values of effective porosity have the effect of increasing ground water velocity and thus decreasing unretarded radionuclide traveltime estimates.

4.3.9 Radionuclide Transport in the Saturated Zone (SZ2)

Risk Insights:

Retardation in the Saturated Alluvium	High Significance
Matrix Diffusion in the Saturated Zone	Medium Significance
Effect of Colloids on Transport in the Saturated Zone	Medium Significance

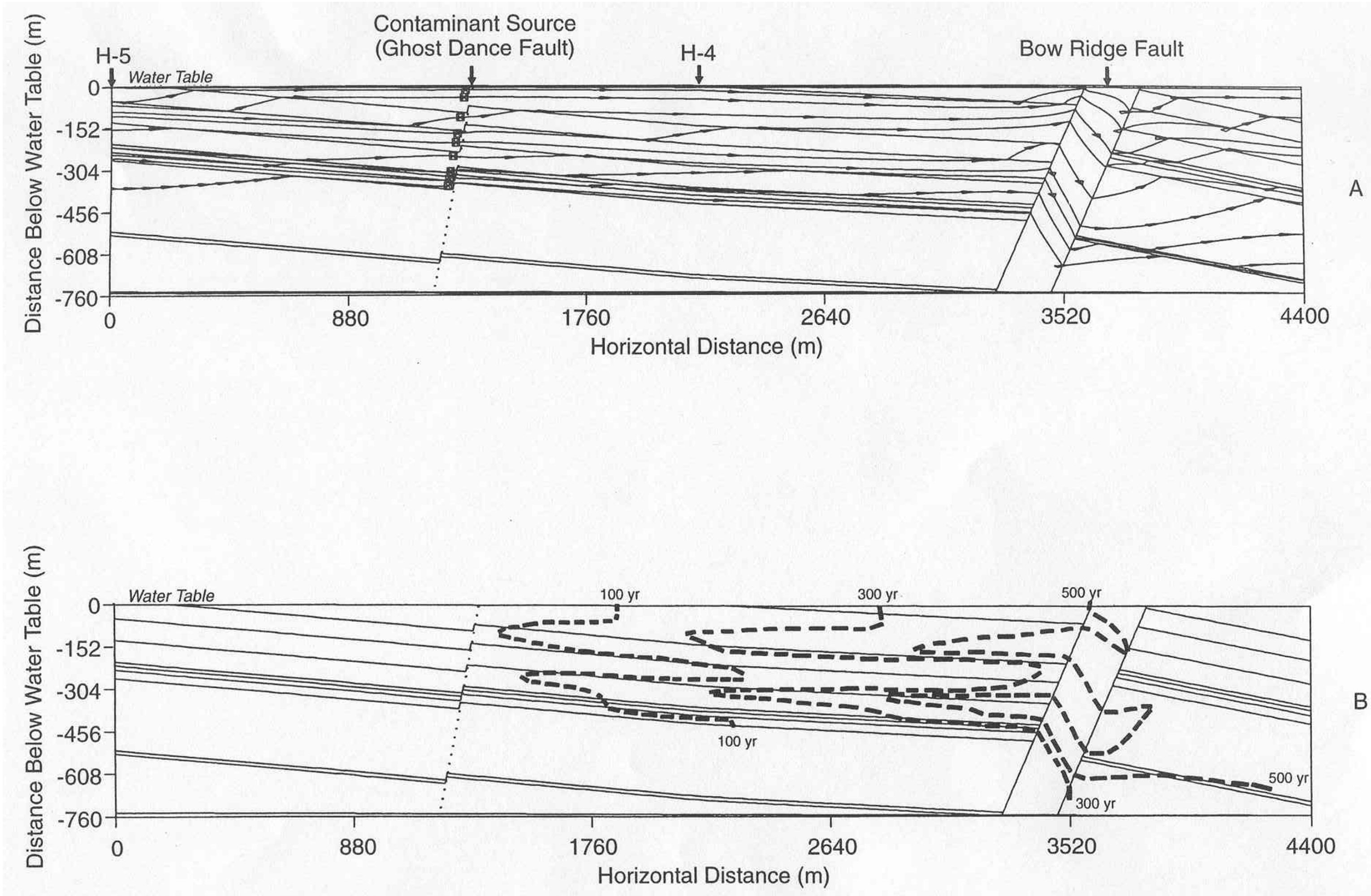


Figure 4-33. Effect of Faults on Pathlines (a) and Unretarded Traveltimes (b) for Vertical Cross-Sectional Flow Model (NRC, 2001, Figure 3-9)

4.3.9.1 Discussion of the Risk Insights

Retardation in Saturated Alluvium: High Significance to Waste Isolation

Retardation in the alluvium unit has the potential to delay the movement of most radionuclides for very long time periods (e.g., thousands to tens of thousands of years and longer) for nuclides that tend to sorb onto porous materials (e.g., Np-237, Am-241, and Pu-240). In this context, Np-237 is the most significant radionuclide affected by retardation in the alluvium, because of the large inventory and long half-life for this radionuclide.

<u>Discussion</u>

The transport of the vast majority of the radionuclides is expected to be significantly delayed by the saturated alluvium, because of chemical sorption on mineral surfaces (Table 4-7). Although certain radionuclides (e.g., I-129 and Tc-99) are not typically sorbed onto mineral surfaces under the geochemical conditions that predominate in the saturated zone, these radionuclides comprise a small fraction of the inventory of spent nuclear fuel (i.e., less than 1 percent). In contrast, radionuclides such as Am-241 and Pu-240, which comprise a majority of the inventory of spent nuclear fuel (Figure 4-1), are characterized by delay times in the alluvium on the order of tens of thousands of years and greater for the full range of expected retardation factors for these nuclides. The range of expected retardation factors for Np-237 is characterized by limited delays (i.e., on the order of 1,000 years) to very significant delay times (i.e., on the order of 100,000 years). Because most radionuclides are retarded or delayed in the alluvium, estimates of dose are typically characterized by the releases of only three radionuclides (I-129, Tc-99, and Np-237). Initial dose is typically from I-129 and Tc-99 and is followed by a later peak from Np-237. The estimated dose from Np-237 tends to be larger than the estimated dose from I-129 and Tc-99 because of the large dose-conversion factor associated with Np-237.

<u>Uncertainties</u>

The DOE sensitivity studies also indicate that the retardation factor used for Np-237 in the saturated alluvium has a significant impact on Np-237 traveltime through the alluvium. The range of the retardation factor used for Np-237 depends on the geochemistry and mineralogy of the saturated zone. Although the retardation factors currently used in the DOE performance assessment of Yucca Mountain likely provide a reasonable estimate of Np-237 sorption, the technical bases for these values are based on experiments with limited accounting of saturated zone chemistry or variation in alluvium mineralogy. The effectiveness of the alluvium in delaying certain radionuclides may be lessened if they are transported as colloids (further discussion of colloids is provided below). Current data for Np-237 transport parameters do not include colloids.

Matrix Diffusion in the Saturated Zone: Medium Significance to Waste Isolation

Matrix diffusion is a somewhat effective process for delaying radionuclides, especially those radionuclides that are sorbed onto rock surfaces (e.g., Np-237, Pu-240, and Am-241). The extent of the rock volume that is available for matrix diffusion, and each radionuclide retardation factor, are the controlling factors.

Discussion

Radionuclides transported within the fractures of the saturated tuff may be delayed because of diffusion from the fracture water into matrix water (i.e., matrix diffusion) when radionuclide concentrations are higher within the fracture water than within the matrix water. This process will affect all radionuclides; however, radionuclides that sorb onto rock surfaces will show longer delays than those radionuclides that are not sorbed. For example, the delay time for Np-237 in the fractured tuff is increased by 1,100 years, when matrix diffusion is varied from low to high effectiveness (Table 4-9). Unlike the unsaturated zone where the flow path is relatively short (i.e., a few hundreds of meters), the saturated zone flow path in fractured tuff is long {i.e., at least 10 km [6.2 mi]} and thus there will be a longer period of time for matrix diffusion to occur.

The inclusion of saturated zone matrix diffusion appears to have only a minimal benefit for lowering dose estimates in performance assessment models. Ziegler (2002), provided in response to a key technical issue agreement, showed comparisons of the median radionuclide transport time for nominal case, in the total system performance assessment for site recommendation, to a case with essentially no matrix diffusion (diffusion coefficient reduced 10 orders of magnitude), and to a case with enhanced matrix diffusion (flow interval spacing reduced 2 orders of magnitude). The results of the comparison showed a significant increase in radionuclide transport time for the most optimistic cases of matrix diffusion, but transport times for the nominal case were not substantially greater than for the case with essentially no matrix diffusion. Winterle, et al. (1999, Figure 2-3) evaluated the effects of matrix diffusion in the saturated zone using the TPA Version 3.2 code. This analysis indicated that the upper bound of the diffusion parameter uncertainty distribution reduced the effective peak dose by less than 10 percent during a 10,000-year performance simulation. (The 10,000-year doses are primarily from I-129 and Tc-99, which are nonretarded radionuclides.)

Uncertainties

Uncertainties in factors that affect matrix diffusion in the saturated zone include the effective spacings between flowing fractures, the extent to which fracture surfaces are coated with secondary minerals, and effective *in-situ* diffusion coefficients for various radionuclides. These uncertainties have led to development of performance assessment abstractions, by both

Table 4-9. Saturated Zone Retardation Sensitivity (with Matrix Diffusion) (Years for Initial Release into Saturated Zone to Exit Saturated Zone)

Nuclide	Alluv {1 km [0.6 mi]} Rf (low) Mat Diff (low)	Alluv {1 km [0.6 mil]} Rf (low) Mat Diff (high)	Alluv {5 km [0.31 mi]} Rf (high) Mat Diff (high)
Tc-99	300	600	700
I-129	300	600	700
Np-237	700	1,800	>100K
Am-241	>100K	>100K	>100K
Pu-240	45,000	>100K	>100K

NRC and DOE, that use conservative or bounding approaches for estimating the effect of matrix diffusion on radionuclide transport.

Effects of Colloids on Transport in the Saturated Zone: Medium Significance to Waste Isolation

Transport of radionuclides attached to natural colloids may reduce the effectiveness of sorption properties of the alluvium.

Discussion

Radionuclides that attach to colloids have the potential to be transported in a manner that may substantially reduce or eliminate the beneficial effects of sorption in the alluvium. The TPA code was used to bound colloid effects by allowing unretarded transport of relatively immobile actinides such as plutonium, americium, and thorium. More realistic approaches for colloids would account for dissolved species as well as colloidally-bound species, reversible sorption onto colloids, and filtration of colloids. That conservative analysis, which assumes a bounding unretarded transport, yielded an increase in dose by more than a factor of 10 (Figure 4-21). However, accounting for more realism is expected to reduce the effects of colloids on dose. DOE has performed analyses to evaluate the sensitivity of colloids where plutonium and americium are irreversibly sorbed to waste-form colloids (Figure 4-22). The DOE analyses indicated that colloidal concentrations were only significant under an intrusive igneous event, wherein a large number of waste packages were significantly damaged. The potential importance of colloidal transport, if all waste packages were to fail within 10,000 years, is evident in the DOE total system performance assessment for site recommendation (CRWMS M&O, 2000b), which indicated colloidal plutonium is the second highest dose contributor after 70,000 years, when a significant number of waste packages are estimated to have failed, allowing release of radionuclides.

Uncertainties

There is uncertainty both with the determination of the colloidal concentration and the extent to which colloids will be transported in the geosphere (i.e., will colloids be filtered as they move through small fracture openings and matrix pores). Some field studies suggest that colloids can travel relatively easily under particular conditions (Kersting, et al., 1999). Sensitivity analyses of colloid-facilitated transport models indicate that filtration is the most important parameter in understanding and estimating the importance of colloids to radionuclide transport (Cvetkovic, et al., 2002).

4.3.10 Volcanic Disruption of Waste Packages (DIRECT1)

Risk Insights:	
Probability of Igneous Activity	High Significance
Number of Waste Packages Affected by Eruption	High Significance
Number of Waste Packages Damaged by Intrusion	Medium Significance

4.3.10.1 Discussion of the Risk Insights

Probability of Igneous Activity: High Significance to Waste Isolation

The risk from igneous activity is directly proportional to the probability of igneous activity. Recent aeromagnetic surveys in the Yucca Mountain region improve estimates of the number of igneous events that have occurred in the past. The number, age, and location of past igneous features are used to constrain the estimates for the probability of future events.

Discussion

Sporadically throughout the past 11 million years, basaltic volcanoes have formed in the region around the potential Yucca Mountain repository site. The probability of igneous disruption is important to risk calculations, because of the relatively low likelihood of future igneous events at the potential Yucca Mountain repository site. Analyses used to demonstrate compliance with licensing requirements must factor the likelihood of a potential disruptive event into the performance calculations, to determine probability-weighted dose. In addition, disruptive events with likelihoods of occurrence less than 1 in 10,000 during the 10,000-year postclosure performance period (i.e., less than 1×10^{-8} per year) do not need to be included in the total system performance calculations. Most DOE estimates for the annual probability of igneous disruption at the potential repository site range from approximately 10^{-10} to 10^{-8} (e.g., CRWMS M&O, 2000). In contrast, alternative probability estimates generally range from approximately 10^{-8} to 10^{-7} (e.g., NRC, 1999), to values as high as 10^{-6} using Bayesian methods (Ho, 1995; Ho and Smith, 1997). None of these models have considered current uncertainties in the number and age of past volcanic events (Hill and Stamatakos, 2002).

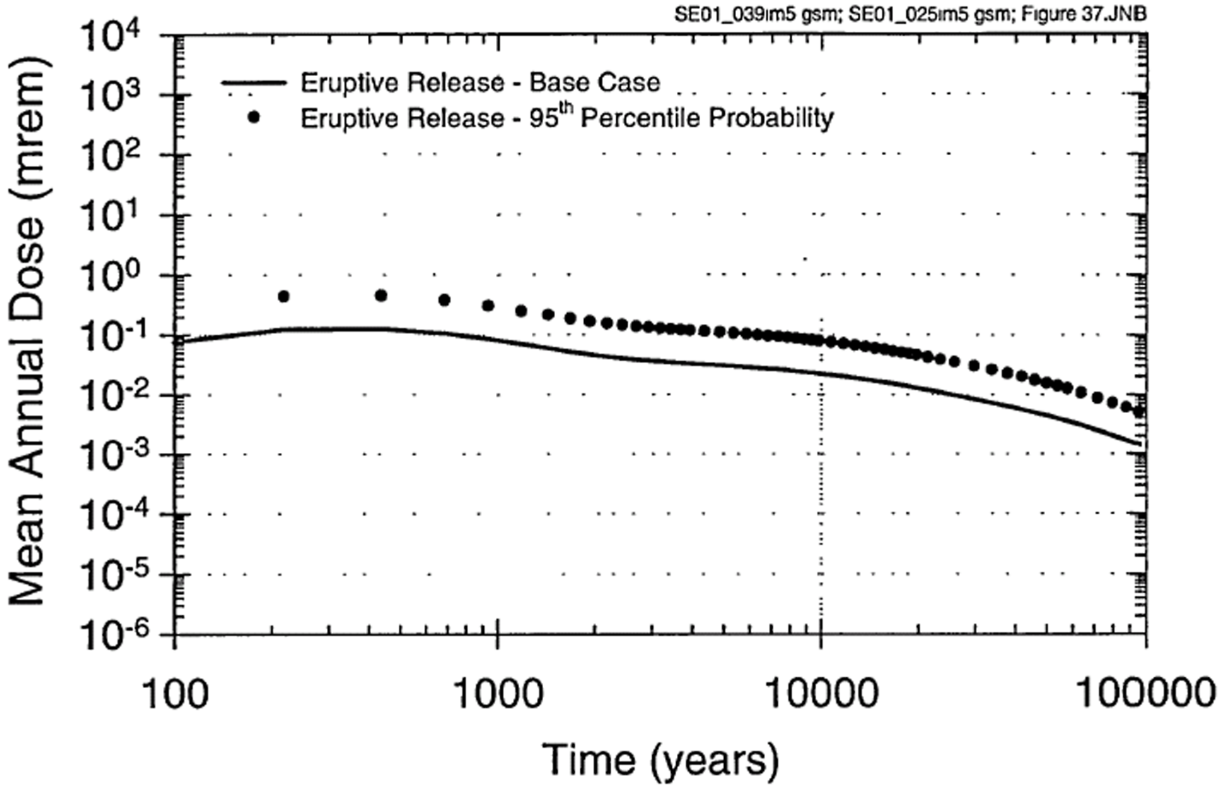
Figure 4-34 shows an increase in the calculated probability-weighted dose from igneous eruption by about a factor of three, when the DOE basecase mean annual probability (1.5×10^{-8}) is replaced by its 95th percentile value (4.8×10^{-8}). This result is consistent with earlier analyses indicating direct proportionality between igneous activity probability and risk (e.g., NRC, 1999; CRWMS M&O, 2000b). Thus, these current differences between the DOE models and alternative probability models may affect igneous activity risk calculations by factors of 10 to 100.

Uncertainties

Potentially significant uncertainties in the probability estimate for igneous activity currently arise primarily from uncertainties in the number, age, and composition of basaltic volcanoes possibly buried around Yucca Mountain. Variations in the size and location of the repository footprint also may increase the probability for igneous activity relative to previously published estimates. Using a range of alternative conceptual models, Hill and Stamatakos (2002) described how these uncertainties may have negligible to order of magnitude effects on probability model uncertainty.

Number of Waste Packages Affected by Eruption: High Significance to Waste Isolation

The consequences of extrusive igneous activity are directly proportional to the number of waste packages intersected by an erupting volcanic conduit. At present, this number is estimated based on observed conduit size at analog volcanoes. Alternative models of how a volcano may



NOTE: Each mean annual dose curve is a probability-weighted average. However, the results of the sensitivity studies do not correspond to expected risk (see introduction to Section 3).

Figure 4-34. Sensitivity of Mean Annual Dose to Igneous Activity Probability. (Bechtel SAIC Company, LLC, 2002, Figure 37. Note that Dose Estimates for Variations from the Basecase Do Not Represent Variations in Expected Risk Because the Probability of the Variation is not Considered) (1.0 mrem = 0.01 mSV)

interact with repository drifts and develop a conduit could increase the number of entrained waste packages and thus increase the concentration of radionuclides in erupted ash.

Discussion

Figure 4-35 shows the sensitivity of extrusive igneous activity dose to the number of waste packages entrained in a volcanic eruption. Normally, in the absence of subsurface drifts, volcanoes form roughly cylindrical conduits along the vertical plane of magma ascent. Based on analogy with deposits at active or deeply eroded volcanoes, staff determined that conduit diameters from 5 to 50 m [16 to 160 ft] represent the most likely range of diameters for a potential future eruption at the potential repository site (NRC, 1999; Doubik and Hill, 1999). In contrast, DOE considers potential conduit diameters up to 150 m [500 ft], albeit with very low likelihoods of occurrence (e.g., CRWMS M&O, 2000; Bechtel SAIC Company, LLC, 2003). Actively erupting volcanic conduits have high temperatures and large physical stresses that most likely would completely disrupt any waste package directly intersected by the conduit

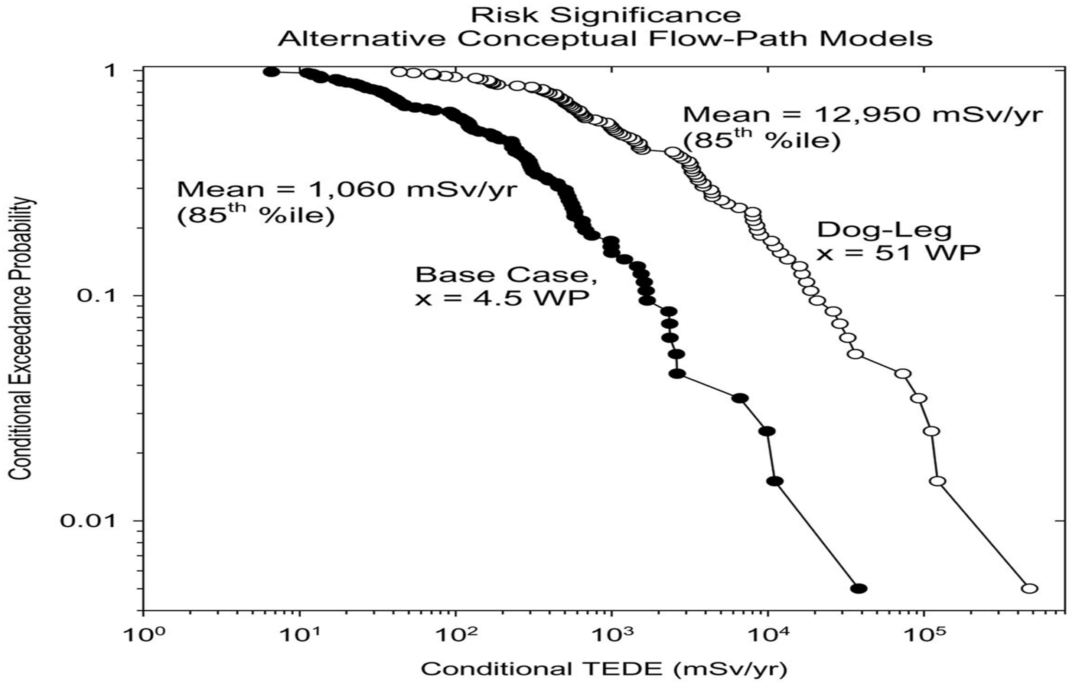


Figure 4-35. Sensitivity of Number of Waste Packages Affected during an Extrusive Igneous Event [Waste Packages (WP), Total Effective Dose Equivalent (TEDE)]

(NRC, 1999; CRWMS M&O, 2000b). Thus, both NRC and DOE have concluded that any waste package entrained in an erupting volcanic conduit would reasonably fail to provide containment and release its contents into the rapidly flowing magma.

Open drifts located at depths of 300 m [1,000 ft] could potentially cause magma ascent and flow processes to behave differently than at undisturbed geologic settings. This is because rising magma is a fluid with an overpressure sufficient to fracture and dilate surrounding wall rock. Intersection with a subsurface drift at essentially atmospheric pressure provides a horizontal pathway out of the original plane of vertical magma ascent, allowing flow localization and nonequilibrium expansion of volatiles (NRC, 1999; Woods, et al., 2002). Using the alternative conceptual model from Woods, et al. (2002), magma could potentially flow down an intersected drift and break out at some point away from the point of original intersection. For randomly located points of intersection and breakout and a single drift containing 155 waste packages, an estimated average of 51 waste packages would be located along the alternative flow path. In contrast, a normal, vertical conduit would intersect an estimated average of 4.5 waste packages using the TPA Version 4.1j code. Figure 4-35 indicates that there is a directly proportional relationship between the number of waste packages entrained and conditional dose (i.e., dose not weighted by the probability of scenario occurrence). This sensitivity appears reasonable, as the mass of high-level waste potentially entrained is relatively small compared to the mass of magma. It is assumed that high-level waste is uniformly distributed in the mass of a modeled eruption; thus, high-level waste behaves as a trace phase in the magma and does not appreciably affect the transport characteristics of a modeled eruption plume (NRC, 1999; CRWMS M&O, 2000b; Bechtel SAIC Company, LLC, 2003).

Uncertainties

In addition to alternative conceptual models for the magma-flow pathway, the number of volcanic conduits created during an igneous event also is uncertain. Using vent location information in Hill and Stamatakos (2002) and assuming medium-to-high confidence magnetic anomalies represent buried volcanoes, it is estimated that there are 17 paired and 13 nonpaired volcanoes in the Yucca Mountain region; most volcano pairs occur in alignments of three to five volcanoes. Volcano pairs have an average spacing of 2.0 ± 1.3 km [1.2 ± 0.8 mi]. Assuming that there is a uniform probability of one, two, or three volcanoes intersecting the repository during a potential extrusive event, and that the overall eruption character remains unaffected by the number of volcanic conduits, dose increases by approximately a factor of two from this process.

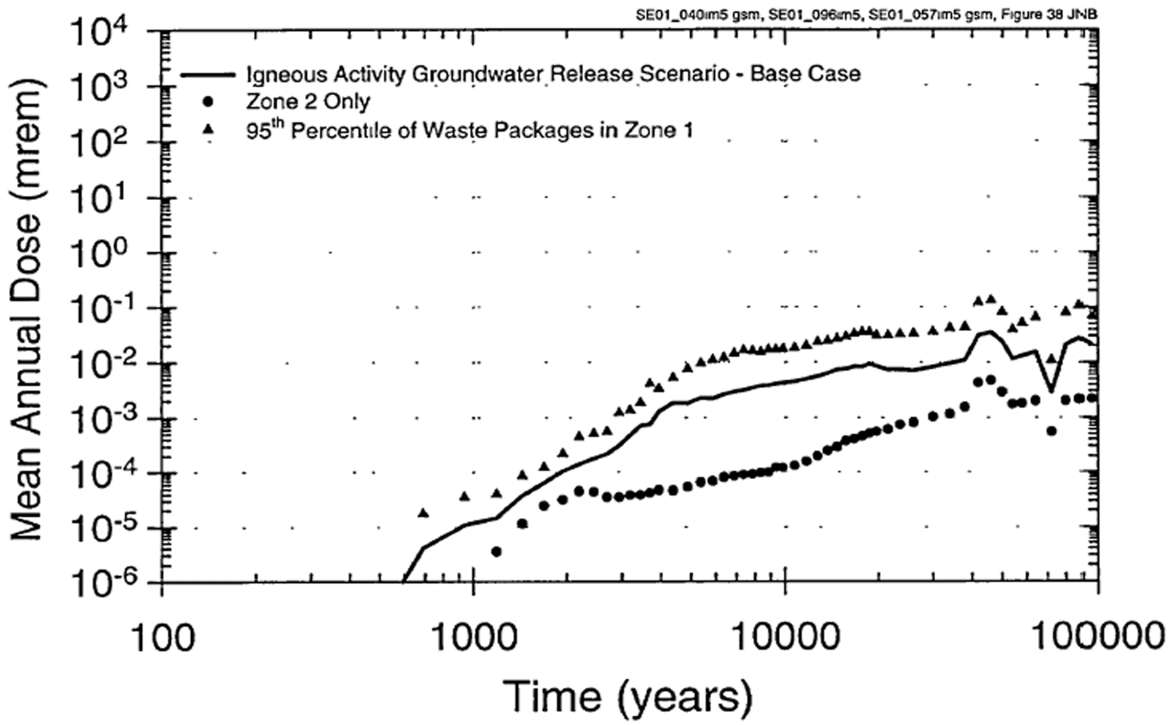
Number of Waste Packages Damaged by Intrusion: Medium Significance to Waste Isolation

The consequences from intrusive igneous activity are directly proportional to the number of waste packages damaged by direct magma flow into intersected drifts. Damage to waste packages likely occurs from the high thermal, mechanical, and chemical stresses created by basaltic magma. Although process models for these effects have not been developed, available information suggests current waste package design may not provide the physical integrity necessary for waste isolation after direct contact with basaltic magma.

Discussion

At depth of 300 m (1,000 ft), rising basaltic magma is a mixture of gas and melt with sufficient overpressure to fracture and dilate surrounding rock to apertures of approximately 1 m [3 ft] wide. If this confined fluid encounters an open or partially backfilled drift at essentially atmospheric pressure, it will preferentially flow into this drift. Depending on the amount of gas expansion, unobstructed flow speeds can range from the order of 10 m/s [30 ft/s] (Lejeune, et al., 2002) to potentially the order of 100 m/s [300 ft/s] (NRC, 1999; Woods, et al., 2002). Thus, intersected drifts could rapidly fill with magma. Based on current understandings of waste package responses to high-temperature, high-mechanical-load environments, waste packages in direct contact with magma will most likely lose physical integrity and provide no further protection against subsequent hydrologic flow and transport (NRC, 1999, 2002; Bechtel SAIC Company, LLC, 2003). In addition, the high temperatures and complex reducing-to-oxidizing chemical environment created by an igneous intrusion may alter the waste, which could result in more soluble waste forms than intact spent nuclear fuel.

Figure 4-36 shows that the estimated dose from igneous intrusion increases by about a factor of 3 when the number of waste packages damaged is increased from a base value of approximately 300 to a 95th percentile value of more than 900. Earlier analyses (Figure 4-37) have shown similar sensitivity of the calculated igneous intrusion dose to the number of waste packages damaged. These sensitivity analyses also do not account for uncertainties in the amount of possible damage to waste packages not directly contacted by magma, but still exposed to potentially corrosive volcanic gasses. Nevertheless, these results indicate that the consequences from releases of radionuclides to the ground water from igneous intrusion are directly proportional to the number of waste packages intersected by magma in a drift. More waste packages damaged by an igneous intrusion lead to higher waste concentrations in the ground water at the reasonably maximally exposed individual location. However, given the low probability of occurrence for this event, the estimated risk due to the effect of magma on a large



NOTE: Each mean annual dose curve is a probability-weighted average. However, the results of the sensitivity studies do not correspond to expected risk (see introduction to Section 3).

Figure 4-36. Sensitivity to Number of Waste Packages Hit During an Intrusive Igneous Event (Bechtel SAIC Company, LLC, 2002. Note that Dose Estimates for Variations from the Basecase Do Not Represent Variations in Expected Risk Because the Probability of the Variation Is Not Considered) (1.0 mrem = 0.01 mSv)

numbers of waste packages is expected to be low {i.e., probability weighted dose is approximately 0.0001 mSv/yr [0.01 mrem/yr] at 10,000 years for 900 damaged waste packages} (Figure 4-36).

Uncertainties

The high temperatures and complex chemical environment created by an igneous intrusion would likely alter the waste form, which could affect subsequent solubility and transport processes. These may be significant depending on uncertainties in the appropriate model for waste dissolution and near-field transport.